

Solid-State Lighting A Practical Primer



FIMS

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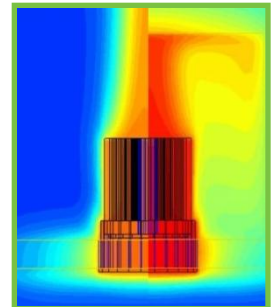
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Learning Objectives

- Critical differences between SSL and other lighting technologies
- Understanding the effect of thermal management on product lifetime
- How to distinguish good from poor SSL products and applications

1. Introduction – Why should I care about LEDs?
2. What's different – LED technology as compared to traditional light sources
3. Technology Limitations – Characteristics to be aware of with solid-state lighting
4. LED Products – Where to turn for guidance
5. Applications – What are the good ones?
6. Final Thoughts – Some general rules



Why Should I Care About LEDs?

- By 2030 the US Department of Energy has estimated that LED technology has the potential to produce yearly energy savings of 190 terawatt-hours
 - Equivalent of 24 large (1,000 MW) power plants
 - Reduction of 25% of present energy consumption for lighting
 - Equates to approximately \$15 billion savings in today's dollars
- Spanning 2010 – 2030, the cumulative energy savings are estimated to total approximately 1,488 terawatt-hours
 - Representing approximately \$120 billion at today's energy prices
 - Over that same time period, greenhouse gas emissions would be reduced by 246 million metric tons

Why Should I Care About LEDs?

LEDs are like no other conventional lighting source

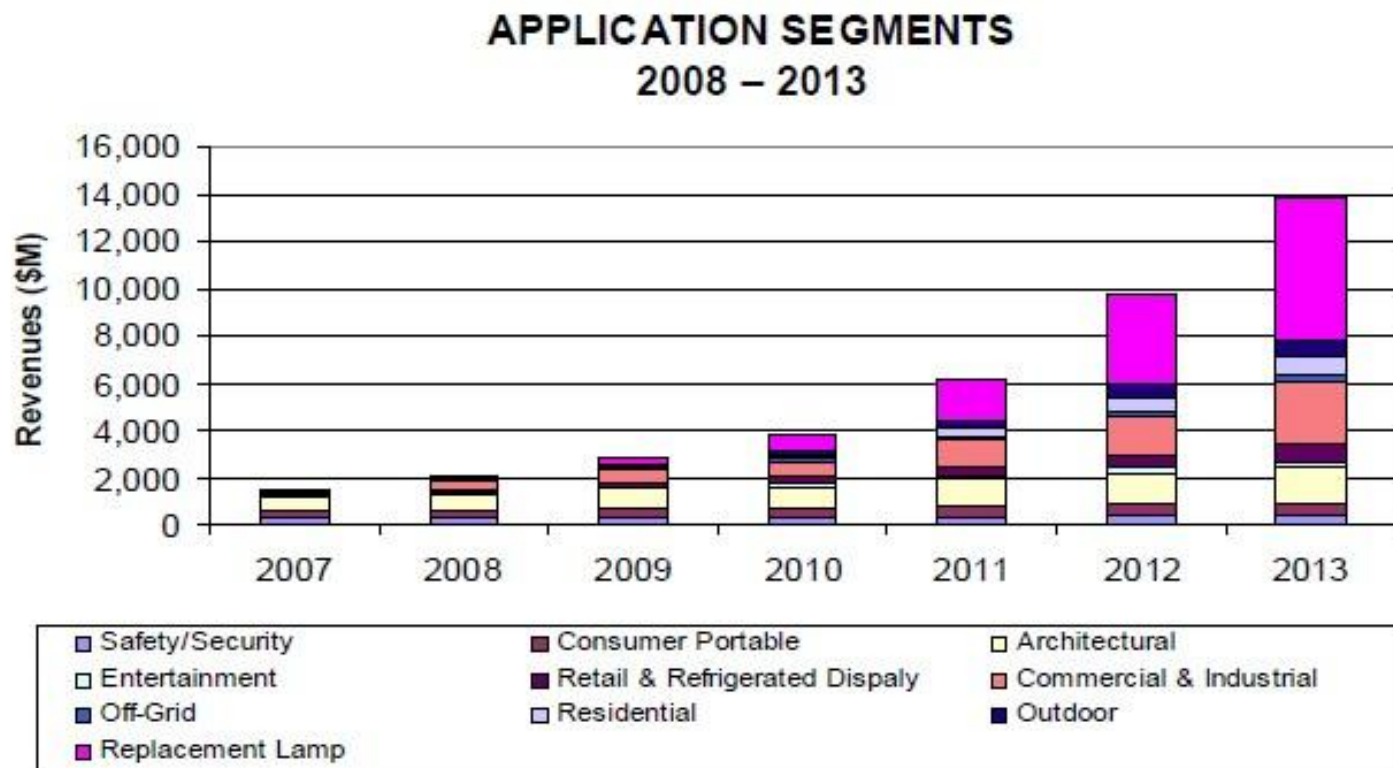
- + Potentially longest¹ life of any lighting sources
- + Very high energy efficiency
- + Small size and instant on allows new applications
- + Produces color light directly without filtering
- + Integrates well with other semiconductor electronic elements
- Thermal management requirements
- Cost
- New technology brings unfamiliar issues to architects, lighting designers, building owners and facilities managers



¹Note: Some manufacturers have introduced products claiming long lifetimes: fluorescent tubes (40,000 hours); induction (100,000 hours)

Why Should I Care About LEDs?

LED market growth over the next 3 years



Source: Vrinda Bhandarkar, Strategies Unlimited

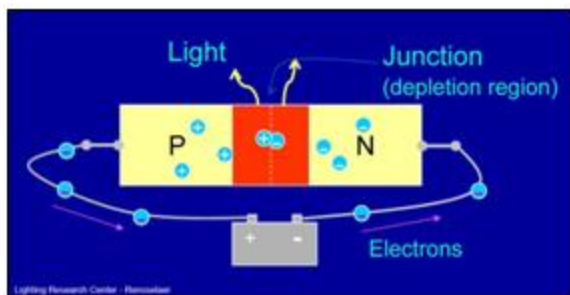
What have you heard about LEDs?

- They don't produce any heat
- They last forever
- Anyone who isn't installing LED-based products everywhere is foolish
- There is a conspiracy to limit the use of LEDs
- There is a conspiracy to force the use of LEDs
- They don't work
- They are too expensive

What is the truth about LEDs?

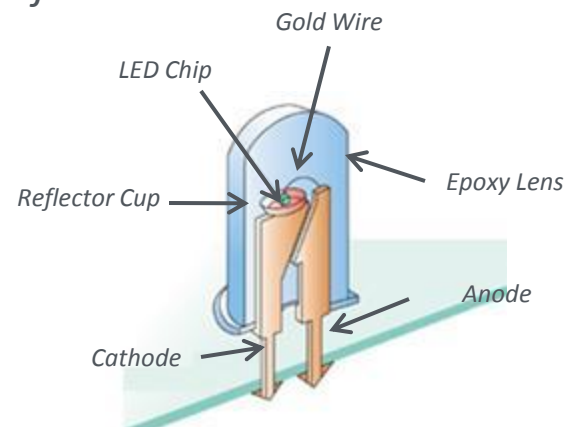
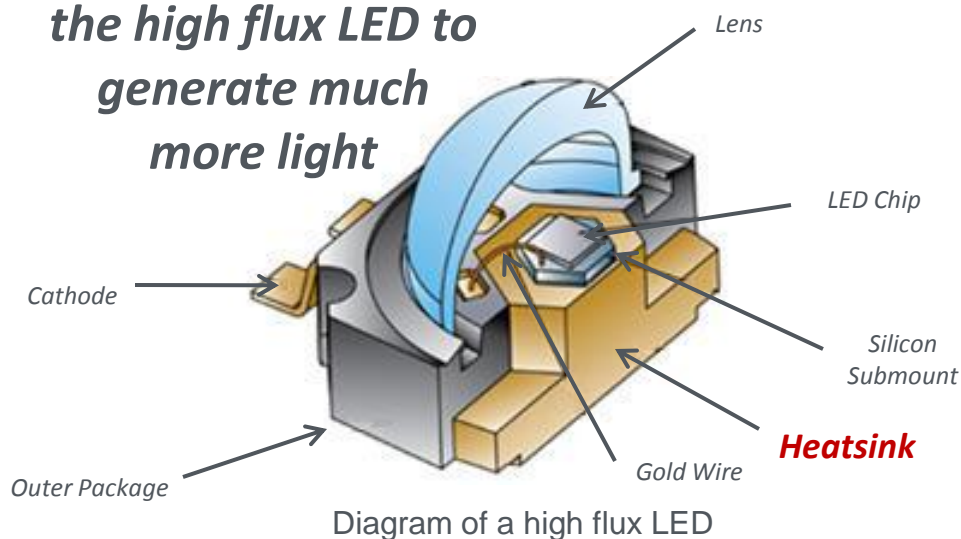
- They **do** produce heat – just not as much
- They **don't** last forever – just longer than other sources
- Anyone who isn't considering installing LED-based products for some applications is foolish
- They don't work if misapplied
- They are expensive but costs continue to drop
- There is a conspiracy by physicists to force the metric system on everyone having nothing to do with LEDs

What is an LED?



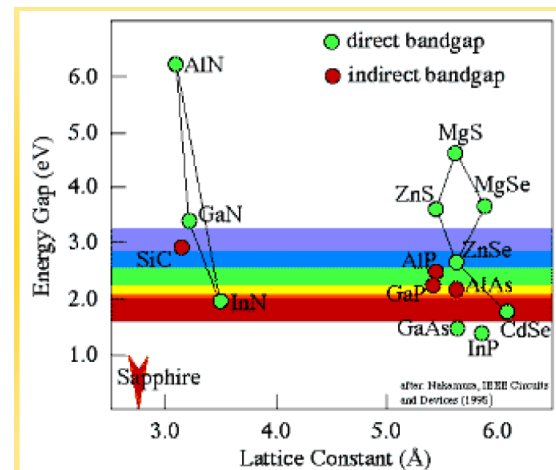
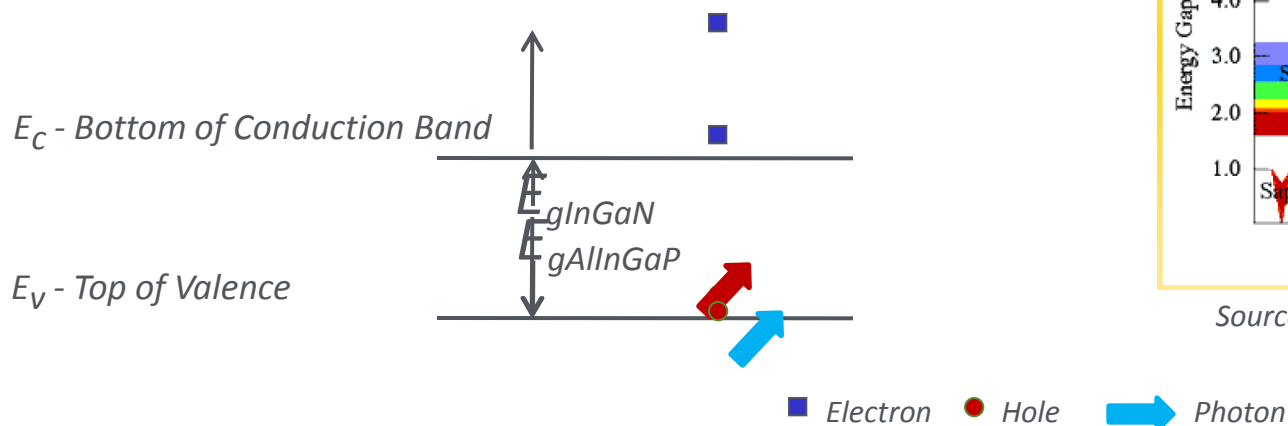
An LED (***L**ight **E**mitting **D**iode*) consists of a chip of semiconducting material treated to create a structure called a p-n (positive-negative) junction

The heatsink is what allows the high flux LED to generate much more light



How does the LED make light?

Bandgaps – Different gaps, different colors



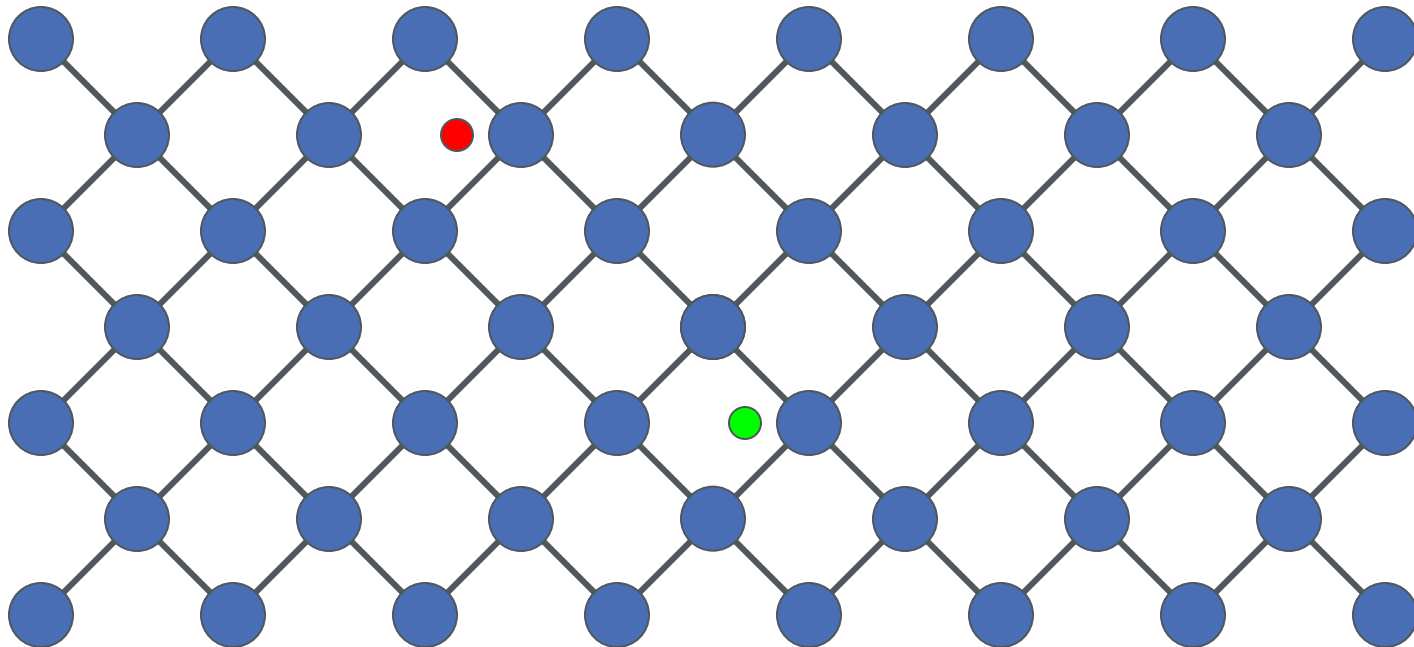
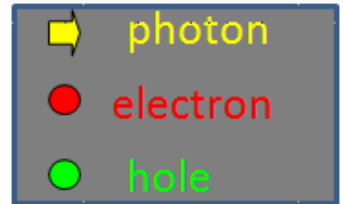
Source: Ian Ferguson, NC University

Smaller bandgap → Lower energy → Longer wavelength photon → Red

Larger bandgap → Higher energy → Shorter wavelength photon → Blue

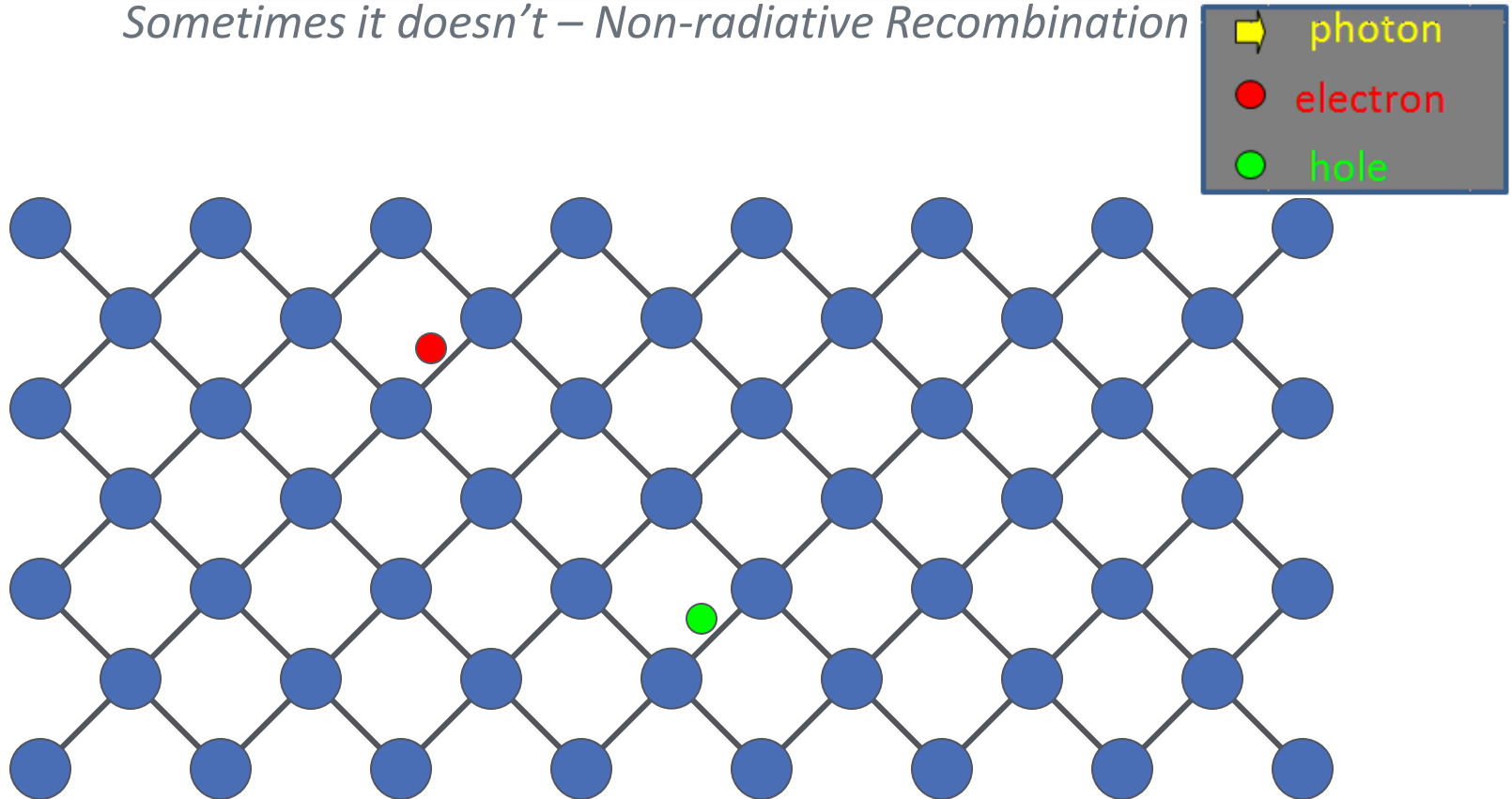
How does the LED make light?

Sometimes it works – Radiative Recombination



How does the LED make light?

Sometimes it doesn't – Non-radiative Recombination

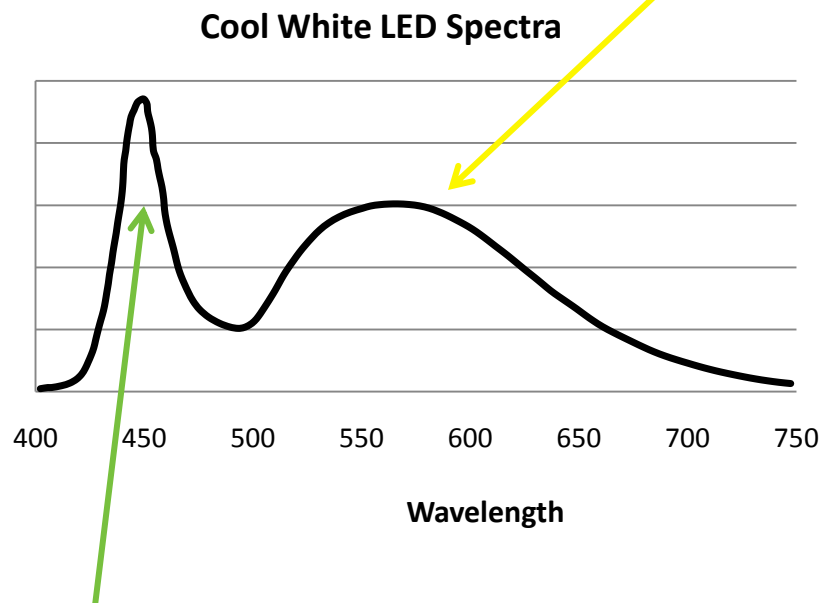
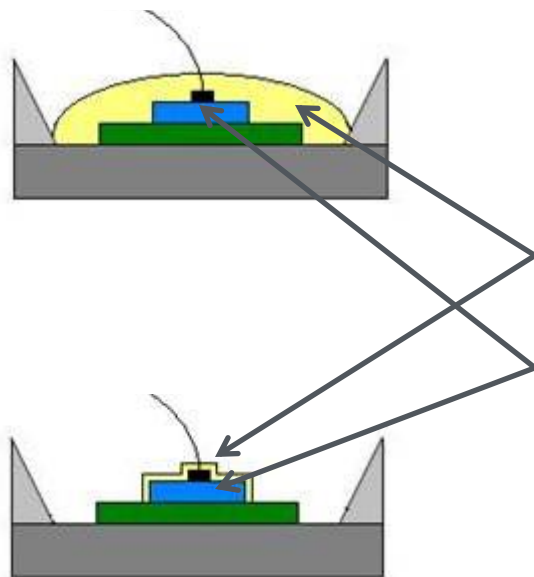


How does a white LED work?

Downconverting Phosphor

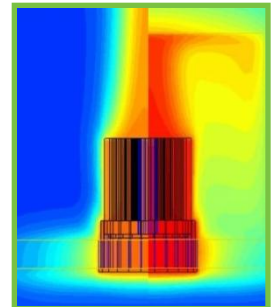
- Blue LED + YAG **Cool White**
- Blue LED + YAG + Other phosphor (red, green, etc.) **Warm White**
- UV LED + Red phosphor + Green phosphor + Blue phosphor

Yellow Phosphor



Blue Die

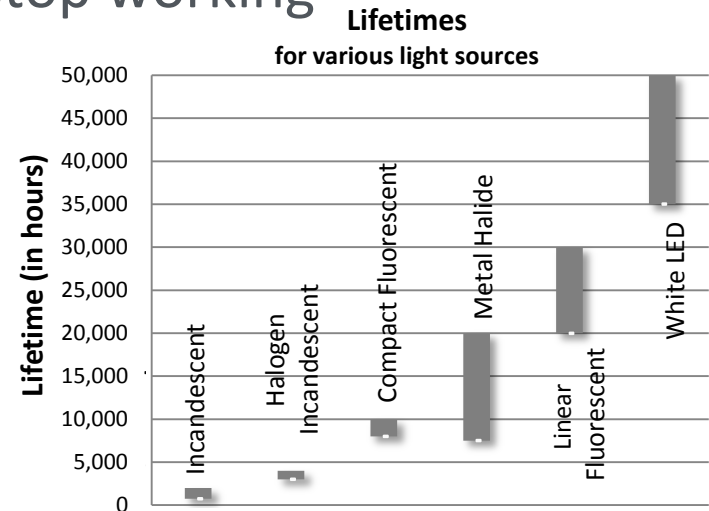
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Long Lifetimes

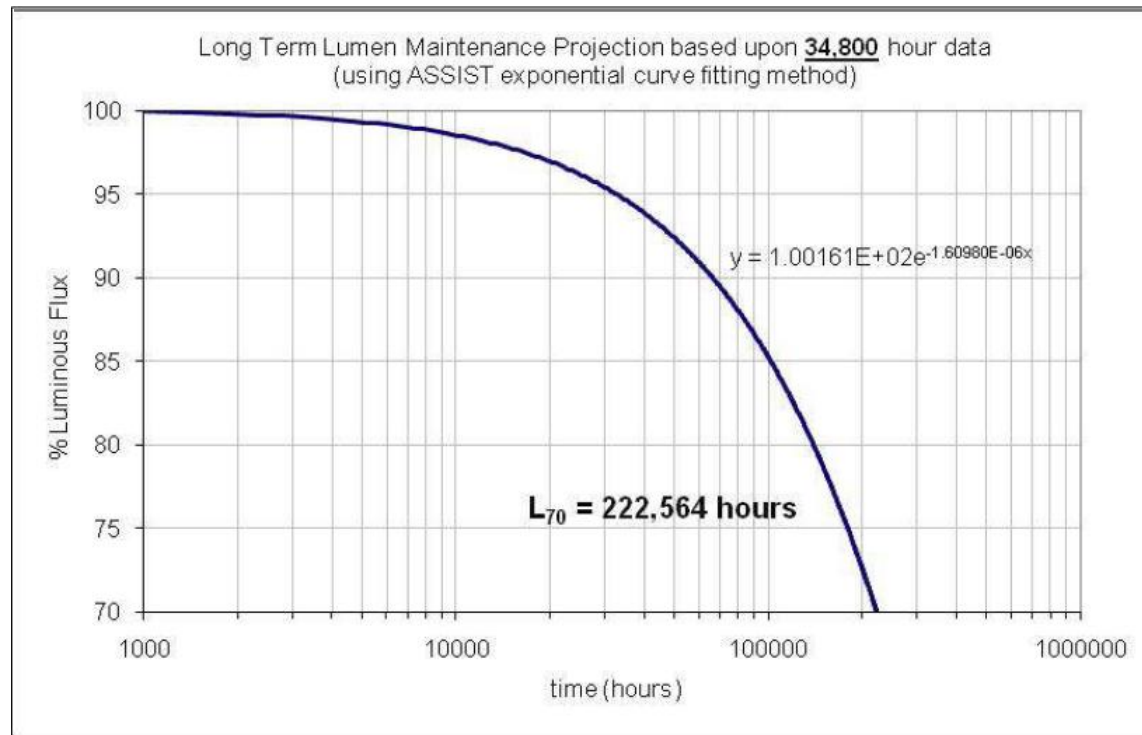
- Traditional light sources fail catastrophically due to electrodes which weaken or become contaminated and eventually fail, causing the lamp to stop working

- LEDs rarely fail catastrophically
 - Light output gradually decreases over operating time
 - End of life defined to be when light output reaches 70% of initial value
 - Raises issue for designers – how to warn users that product has exceeded end-of-life and is producing less light than the application may require
 - Lifetime highly dependent on temperature (ambient and device as well as operating current)



Long Lifetimes – A Measurement Issue

- It is difficult to predict the long term performance of a device with only early lifetime data

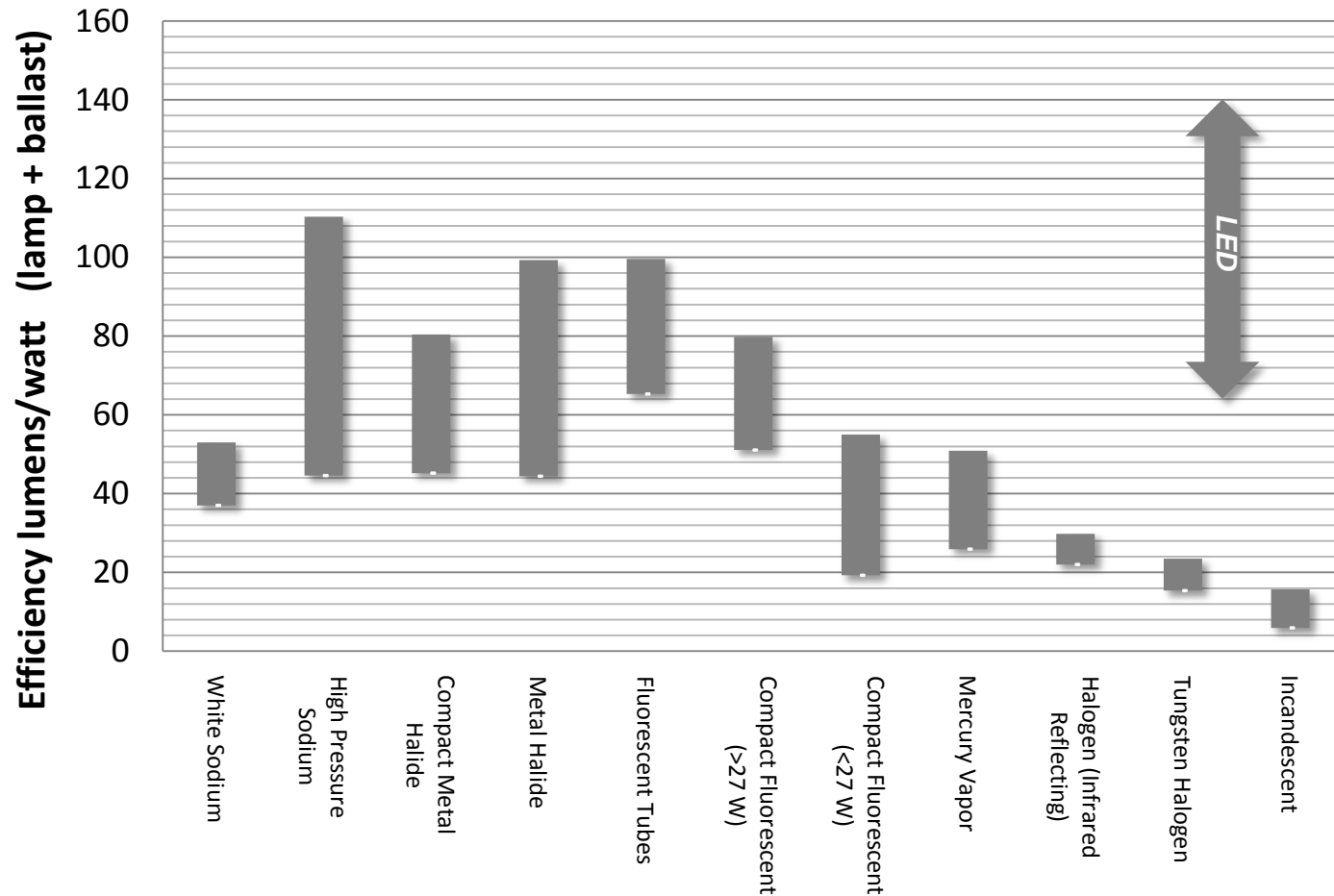


Source: Cree

34,800 Hours
~~off data~~

**Almost 3.5 X's
longer predicted
lifetime than
the 6,000 hour
results**

Highest Energy Efficiency



Small Size



T5 Fluorescent

1350 lumens

75W PAR 38 Halogen

1100 lumens



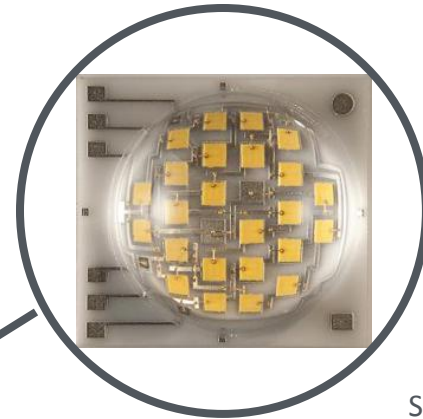
75W Incandescent

1200 lumens



Cree MP-L LED

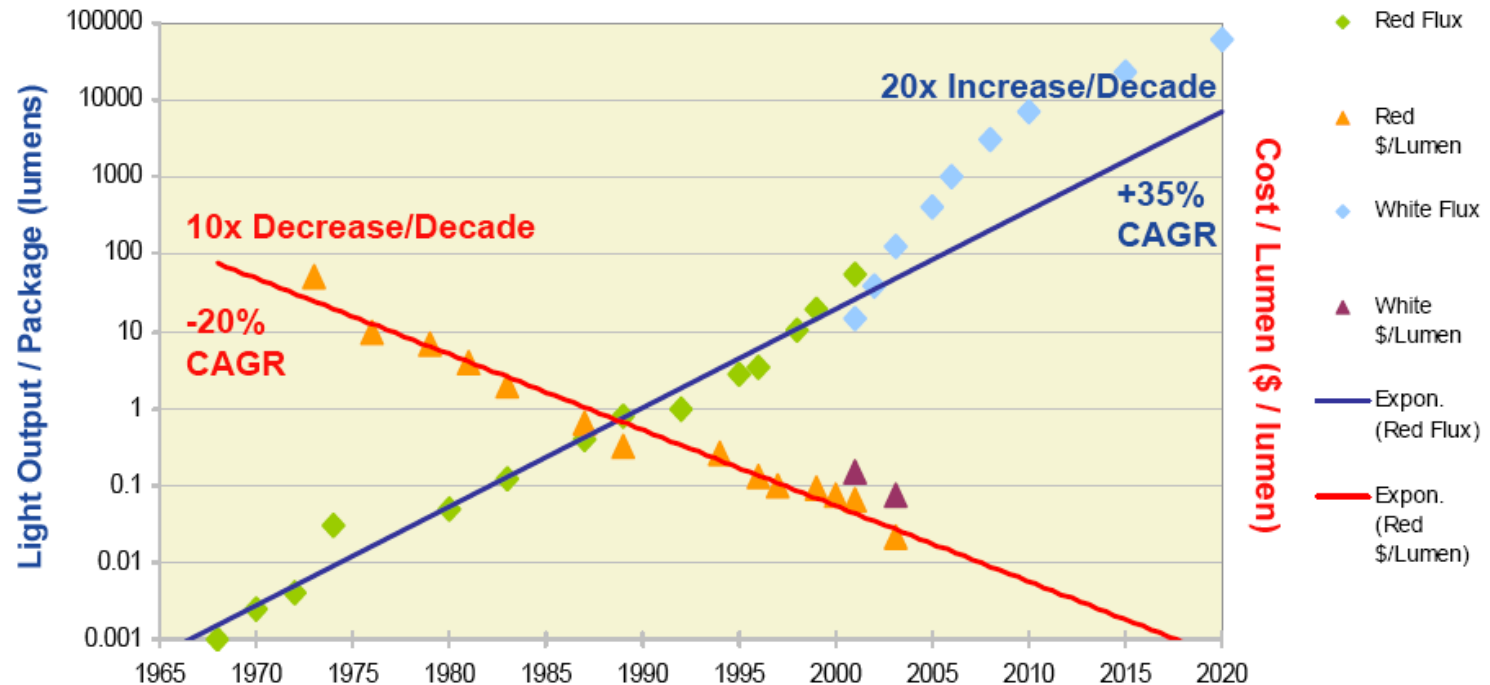
1200 lumens



Source: Cree

Rate of Development

LEDs follow a development rule known as Haitz's Law



Source: Roland Haitz & Lumileds

New Names and Shapes in Lighting

Traditional Lamp Suppliers

- Sylvania
- Philips
- GE



LED Suppliers

- Osram
- Lumileds
- Cree
- Bridgelux
- Nichia
- Seoul Semiconductor
- Toshiba
- Sharp
- Toyota Gosei
- Edison Opto
- and many more...



Direct Color Creation

- For color lighting applications, traditional light sources use energy to create white light which then is filtered to create the desired color. The energy used to create the other colors is wasted

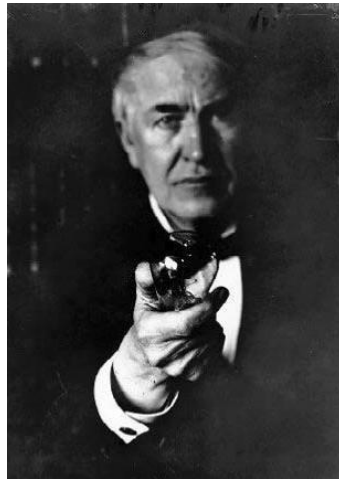


- LED light sources create the color directly leading to greatly improved energy efficiency



Obsolescence — Part of the economic picture

- If Edison were alive today, he would certainly recognize his light bulb




- If you owned this fixture, you could still get lamps for it



Early 20th century
light fixture

Obsolescence – Some things don't change

A 1942 Magazine ad for General Electric
fluorescent lamps 

A 2007 news release from a lighting magazine on an improved fluorescent lamp

Philips Lighting introduces revolutionary new Alto II linear fluorescent lamp technology

Date Announced: 06 Sep 2007

SOMERSET, N.J. - Philips Lighting Company, a division of Philips Electronics North America Corporation, an affiliate of Royal Philips Electronics (NYSE: PHG, AEX: PHI), proudly announces the introduction of ALTO II, its next-generation low-mercury fluorescent lamp technology for the professional lighting market.

Twelve years ago, Philips Lighting introduced its original ALTO technology and set a new industry standard by reducing the amount of mercury in its T8 fluorescent lamps to an industry low of 3.5 mg.

Today, through Philips Lighting's innovative technology, ALTO II T8 lamps now contain only 1.7 mg of mercury, an unprecedented 50 percent reduction from previous levels.

Now incorporated into a variety of 32-Watt Philips T8 lamps, lamps with ALTO II technology will continue to deliver the same high performance as the previous generation of ALTO lamps.

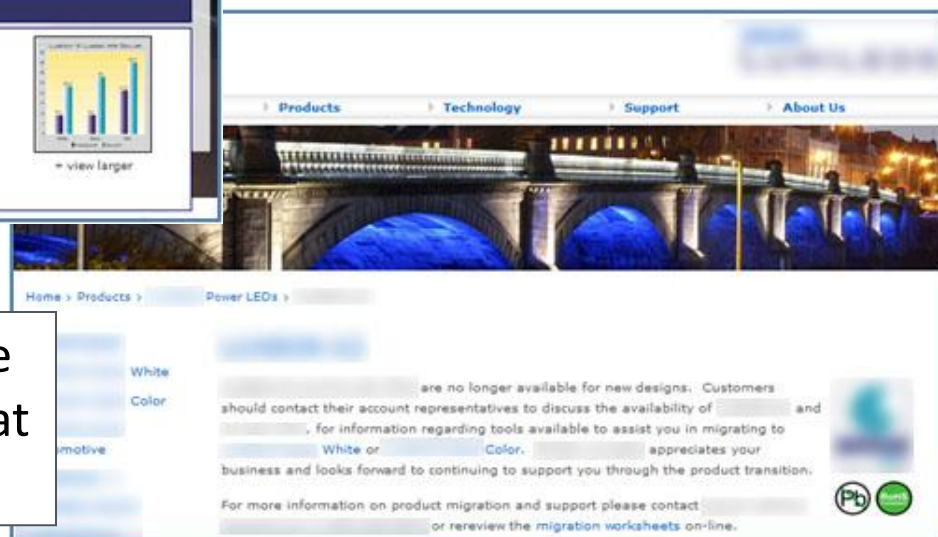


Obsolescence — And some things do



Manufacturer's web site from February 2006 showing the addition of a new line of LED devices

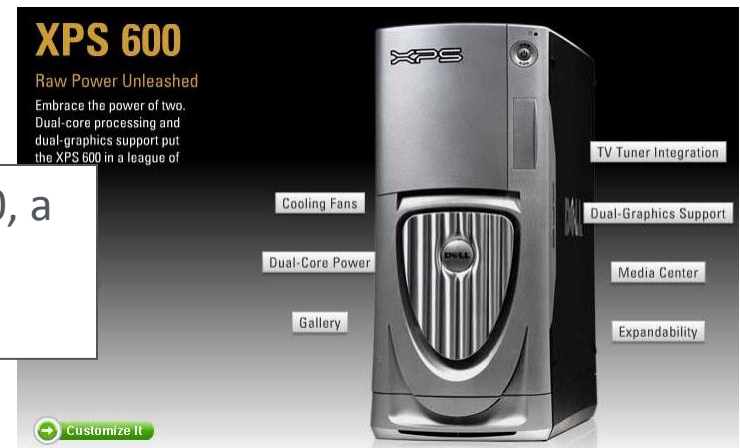
The same manufacturer's web site from March 2010 discontinuing that same line of LED devices



Obsolescence — Rapid change is common for some industries

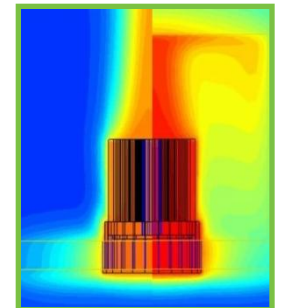
This is nothing unusual for the semiconductor
and electronics industries

Try calling Dell computer and ordering an XPS 600, a
model available in 2006 when the previously
mentioned LED was introduced



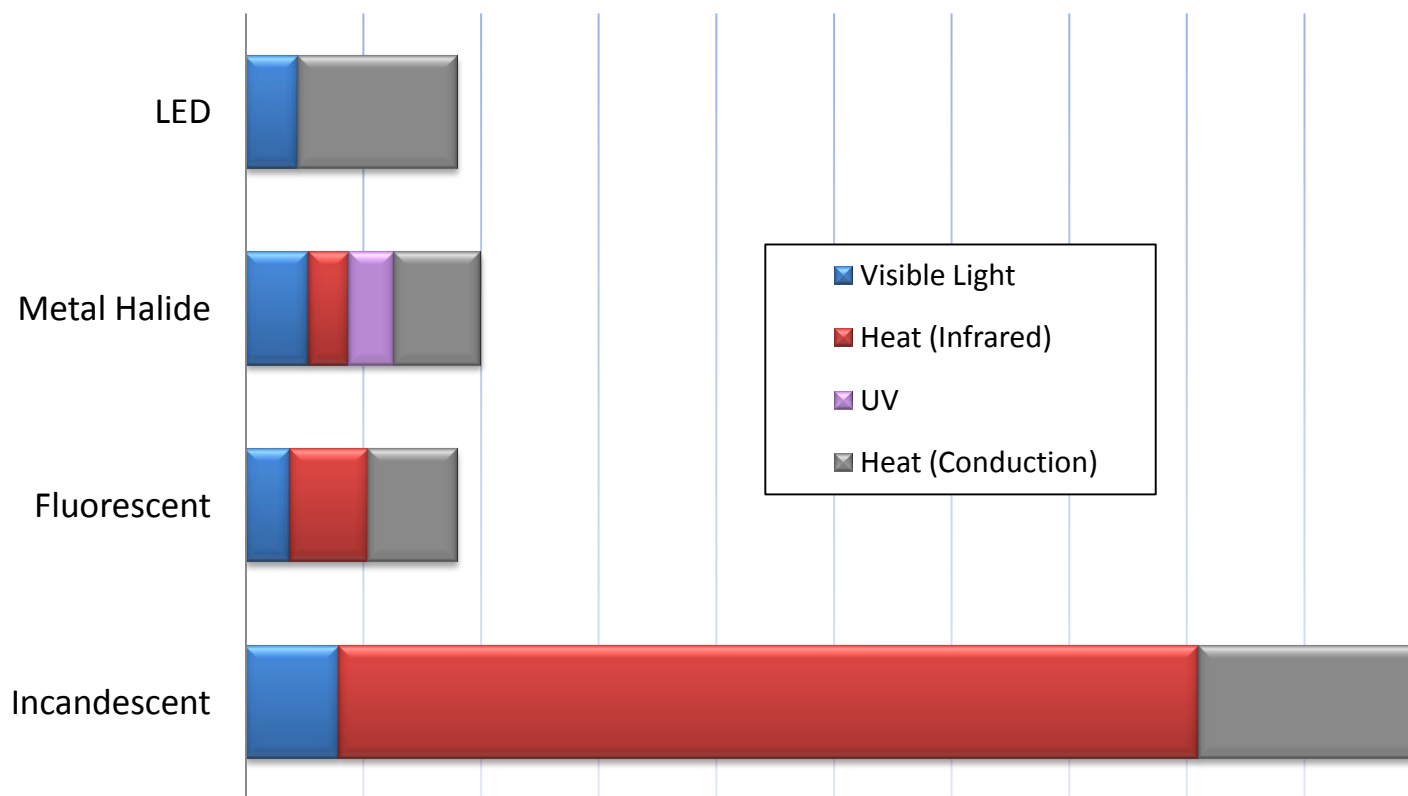
Or try to buy HD-DVD disks for the Toshiba
player also introduced in 2006

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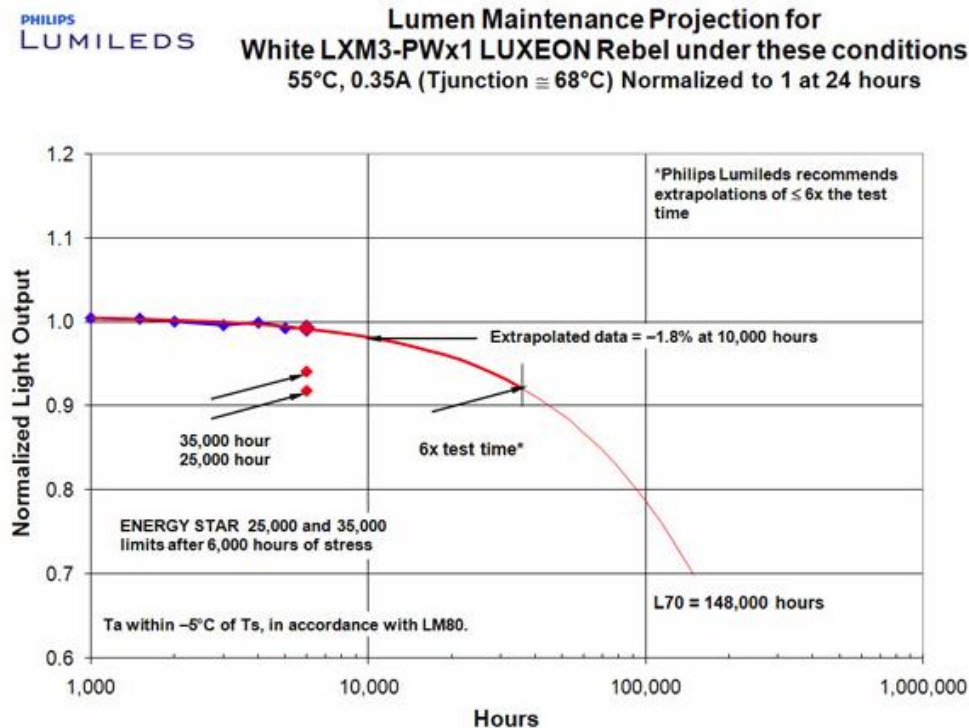
Heat Generation

Power Conversion Comparison For Various Light Sources



Effect of Heat on Lifetime

LED Lifetime with ambient temperature of 85°C is 67,800 hours



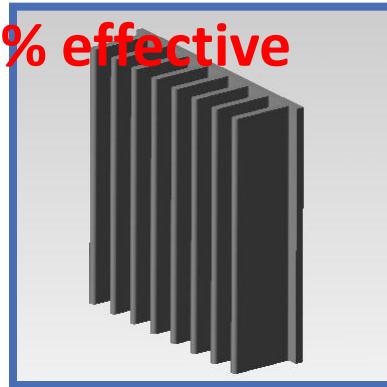
Source: Lumileds

Luminaire Orientation Can Effect Lifetime

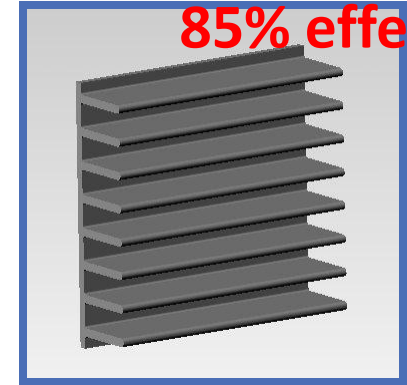
Luminaire manufacturers must take desired orientations into account when designing thermal management system for products

LM-79 testing standard requires the luminaire be tested in the orientation in which it will be mounted

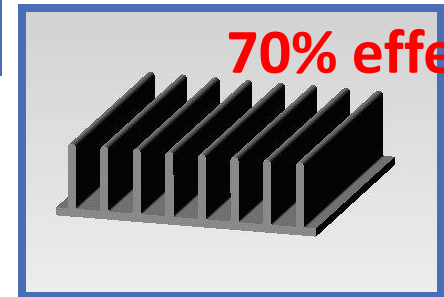
100% effective



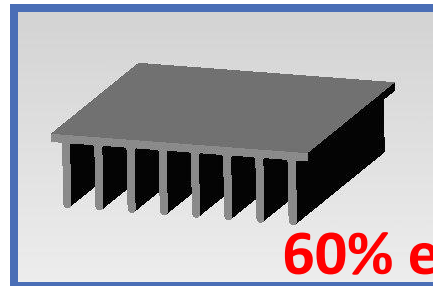
85% effective



70% effective



60% effective



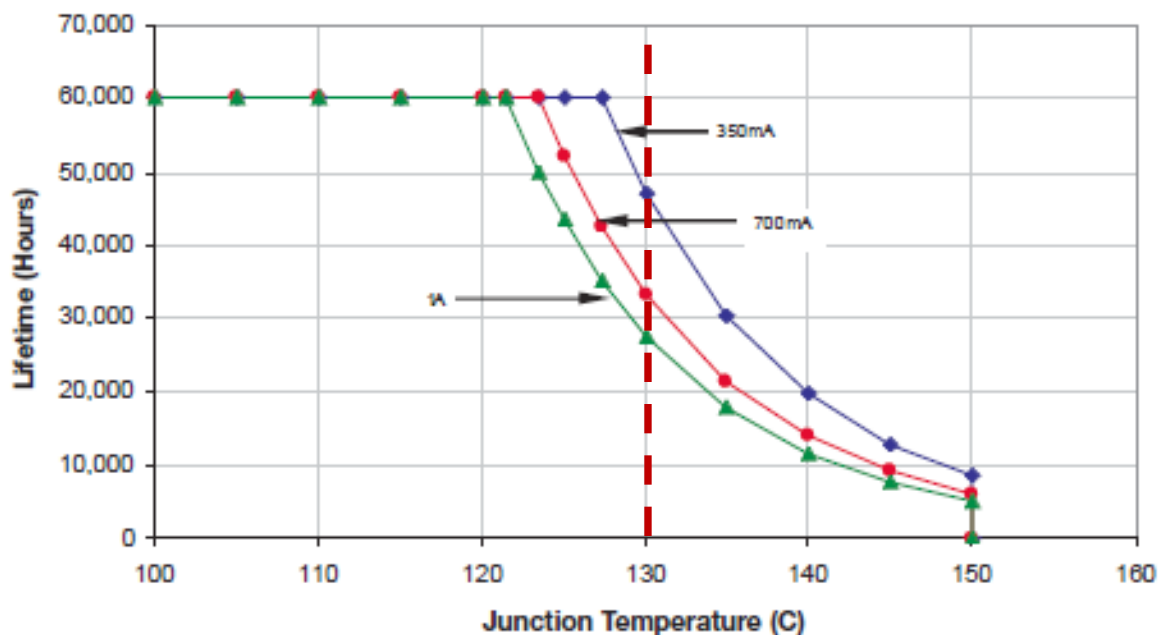
Effect of Drive Current on Lifetime

At a junction temperature of 130°C lifetime is

28k hours (1 A)

33k hours (0.75A)

48k hours (0.350A)

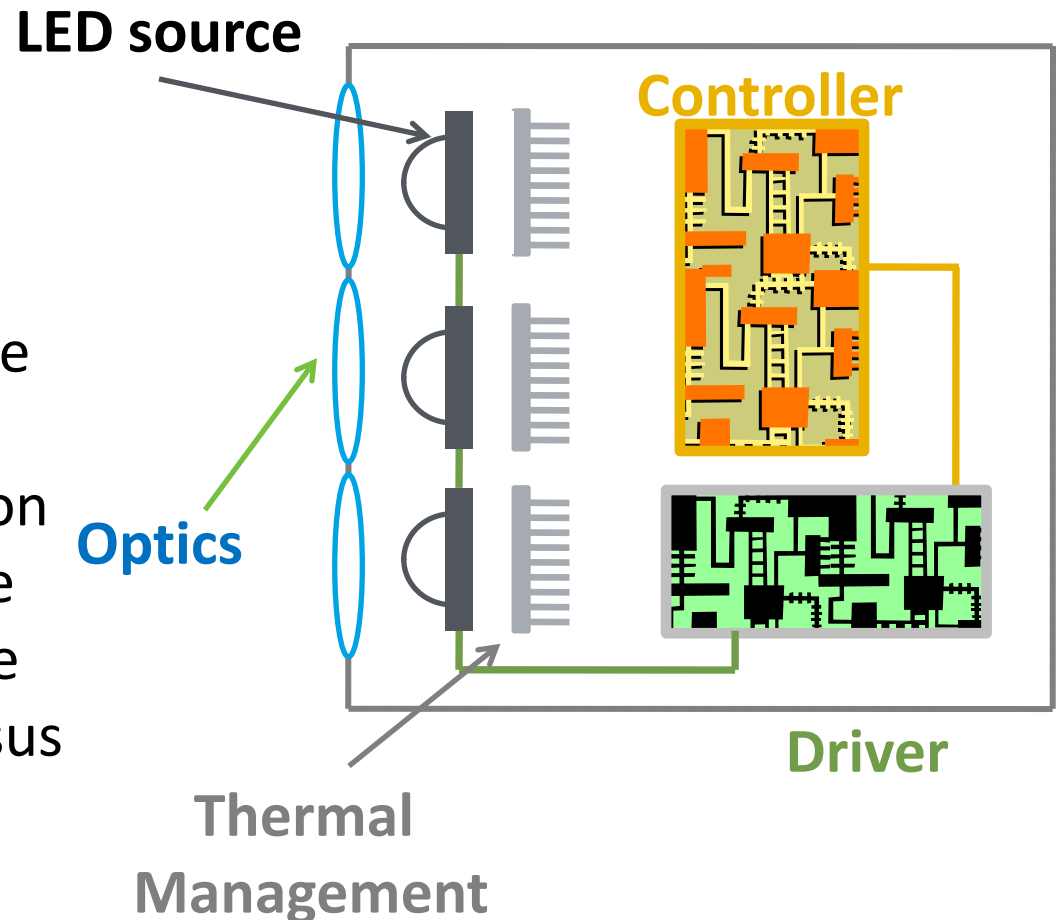


Source: Lumileds Data Sheet

Luminaire Lifetime — A Luminaire is a System

The failure of any one component can cause the entire system to stop functioning

Luminaire designers make trade-offs among the components, depending on the desired performance criteria – for example the number of LEDs (\$\$\$) versus drive current (lifetime)

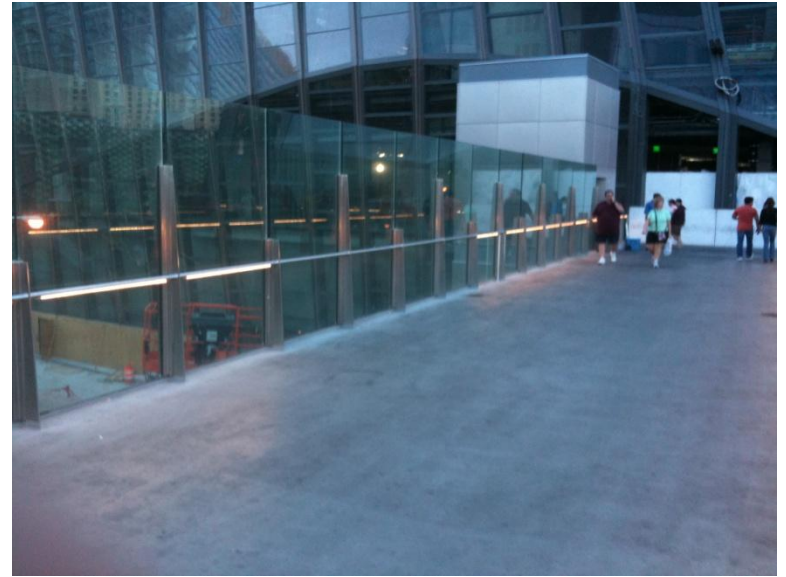


Luminaire Lifetime — A Luminaire is a System

Two examples of failures caused by the driver



NJ Supermarket Freezer Case



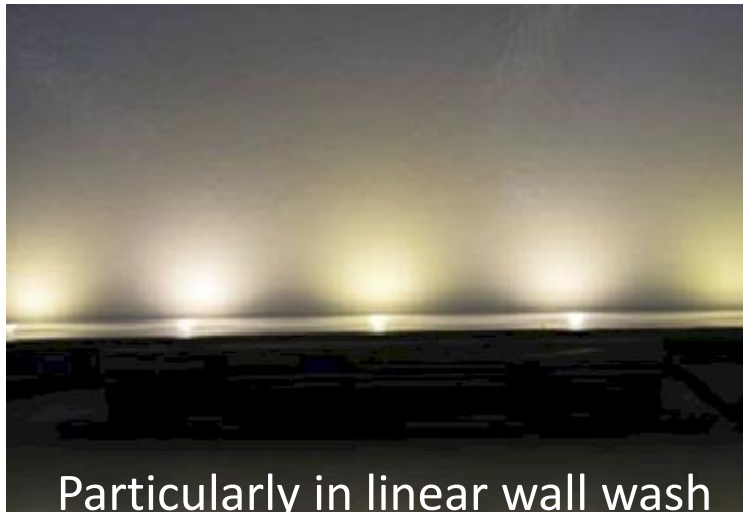
City Center, Las Vegas

Source: LED Transformations

Color Matching / Color Shift

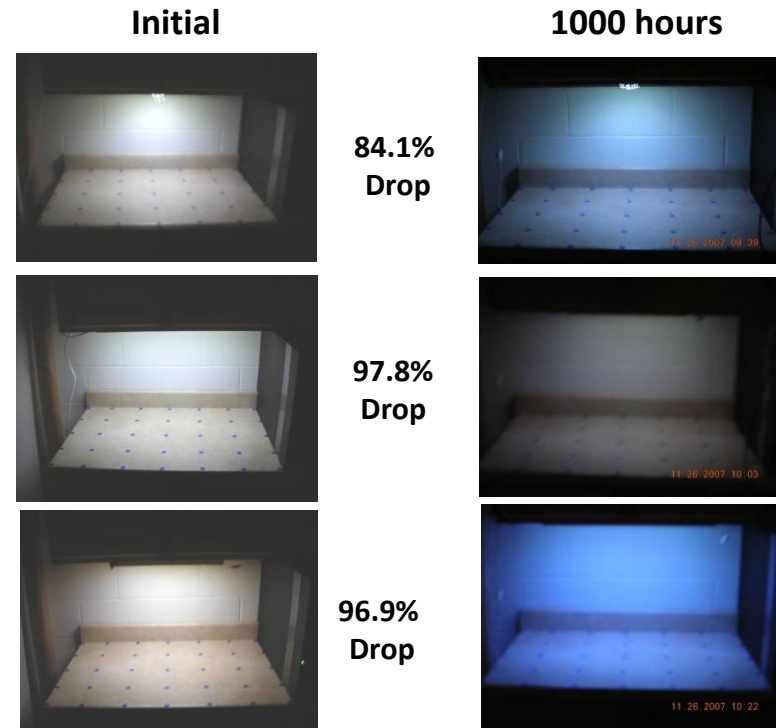
Supplier quality and testing is critical to successful projects

White is white is white?



Particularly in linear wall wash applications, this lack of color consistency is non acceptable

Is blue?



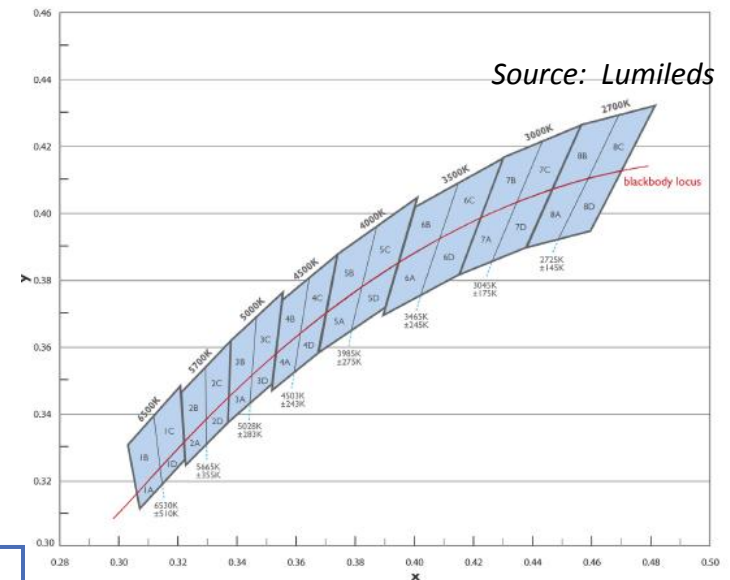
Source: Cree

Color Binning

Solid-state lighting manufacturers cannot control the exact color characteristics of LEDs when they are fabricated. To compensate they sort the finished LEDs into color bins.

Customers purchasing the widest range of bins get the lowest prices. It then becomes their responsibility to produce consistent color products.

At least one manufacturer with a multi-chip product is mix and matching within the device to provide consistent color.



Source: Cree

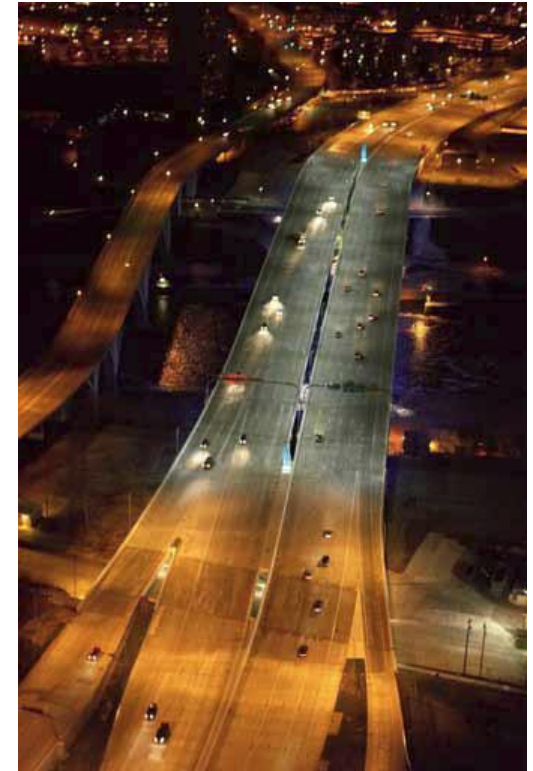
Luminaire Lifetime — A Luminaire is a System

From the original DOE Gateway Report:

- “At the prevailing average nighttime temperature in Minneapolis, the manufacturer projects that the luminaires would need to operate for several decades to reach this level of lumen depreciation [70% of original lumen output], estimating only about a 12% loss after 20 years.”

From a recent interim DOE Report:

- “Continuing decrease detected in average illumination on the ground, roughly 12% from initial after a few [15] months.”



I-35 Bridge, Minneapolis, MN

Luminaire Lifetime – A Luminaire is a System

- **Reason #1:** “Earlier design used an optical gel to fill void between LED lens and proprietary *nano-optic*. Over time, a bubble forms in the gel that causes step change in both lumen distribution and output. The measured optical gel impact on these two samples corresponds to 6.6% and 7.4% reductions in total lumen output.”
- **Reason #2:** Dirt Depreciation

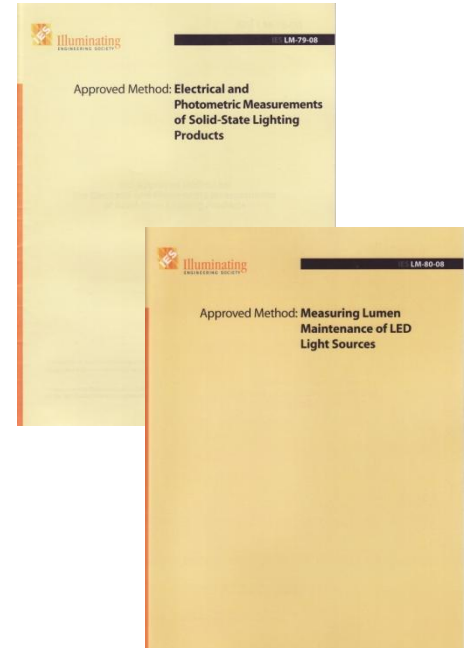


Site	Years of Operation	Lumen Output (Dirty Lens)	Lumen Output (Clean Lens)	Lumen Dirt Depreciation
I-35W	1.25	14520	15227	4.60%
I-35W	1.25	14670	15245	3.80%

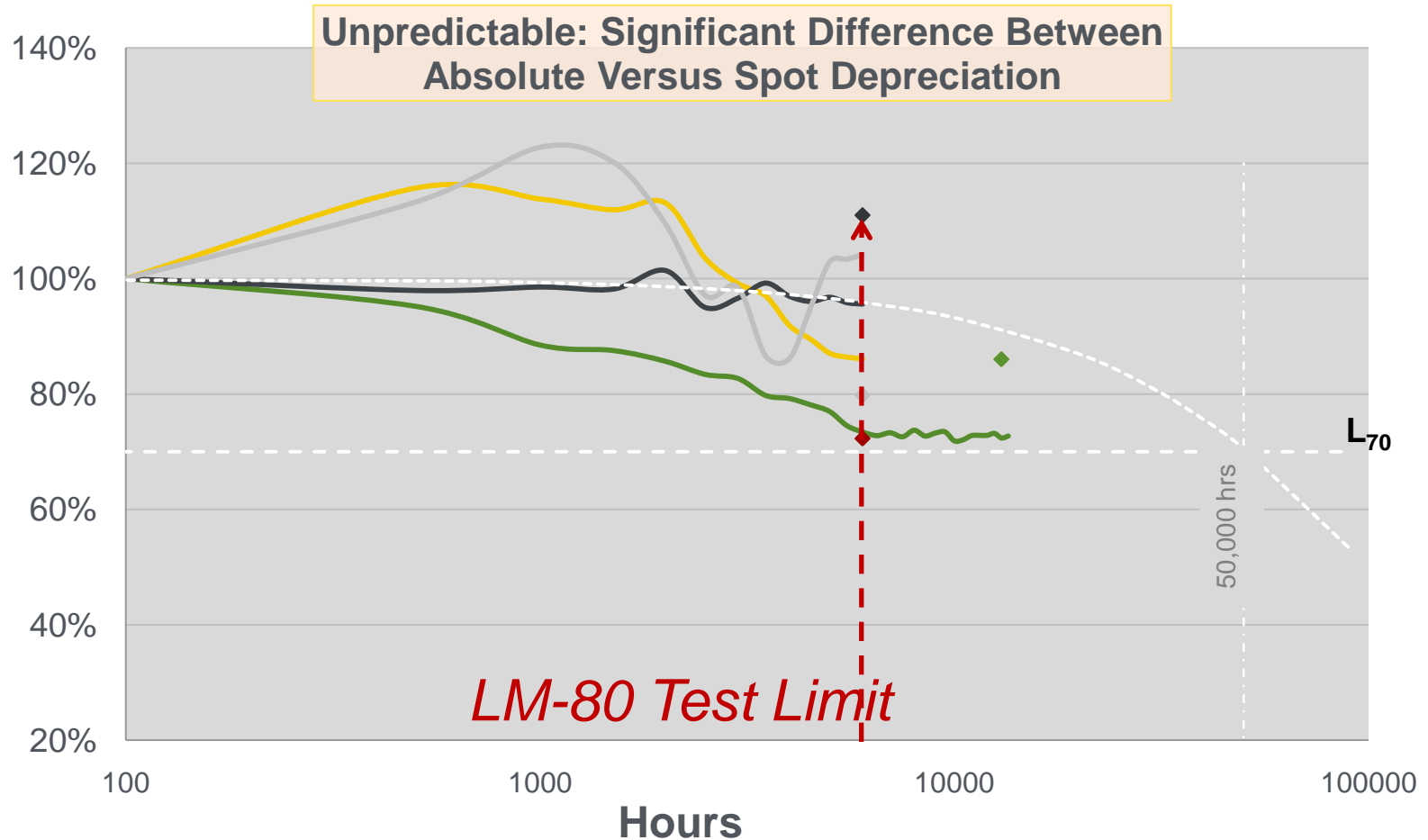
Dirt buildup alone limits lifetime to < 9 years

Standards

- LM-79-08 *Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products*
 - Describes testing procedure for evaluating light distribution from LED-based luminaires
- LM-80-08 *Approved Method for Measuring Lumen Depreciation of LED Light Sources*
 - Describes testing procedure for measuring lumen depreciation of LED devices
 - Does not describe how to evaluate data taken
- No approved standard available for driver lifetimes



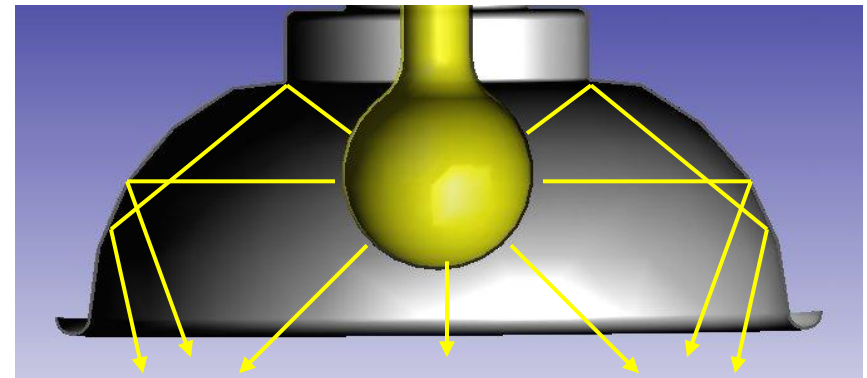
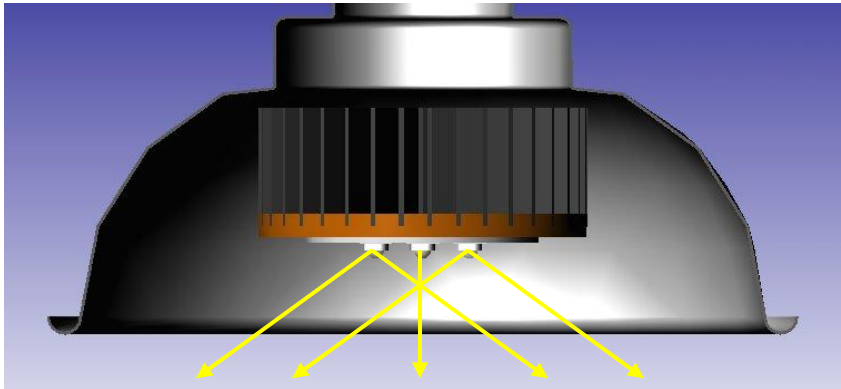
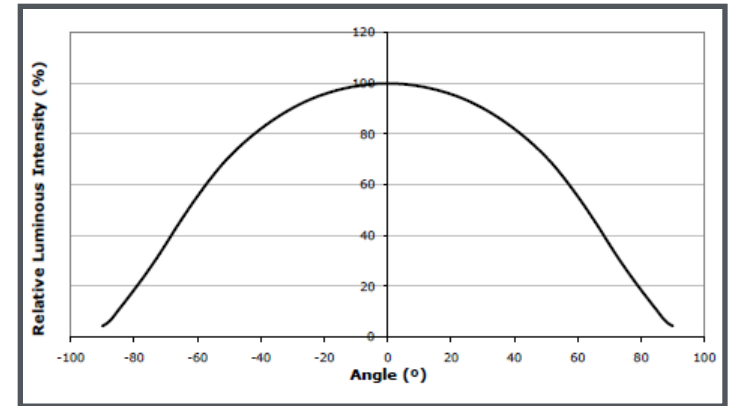
Lifetime — Initial Depreciation Results Can Vary Greatly



CALiPER Round 10 data, www.ssl.energy.gov/caliper.html

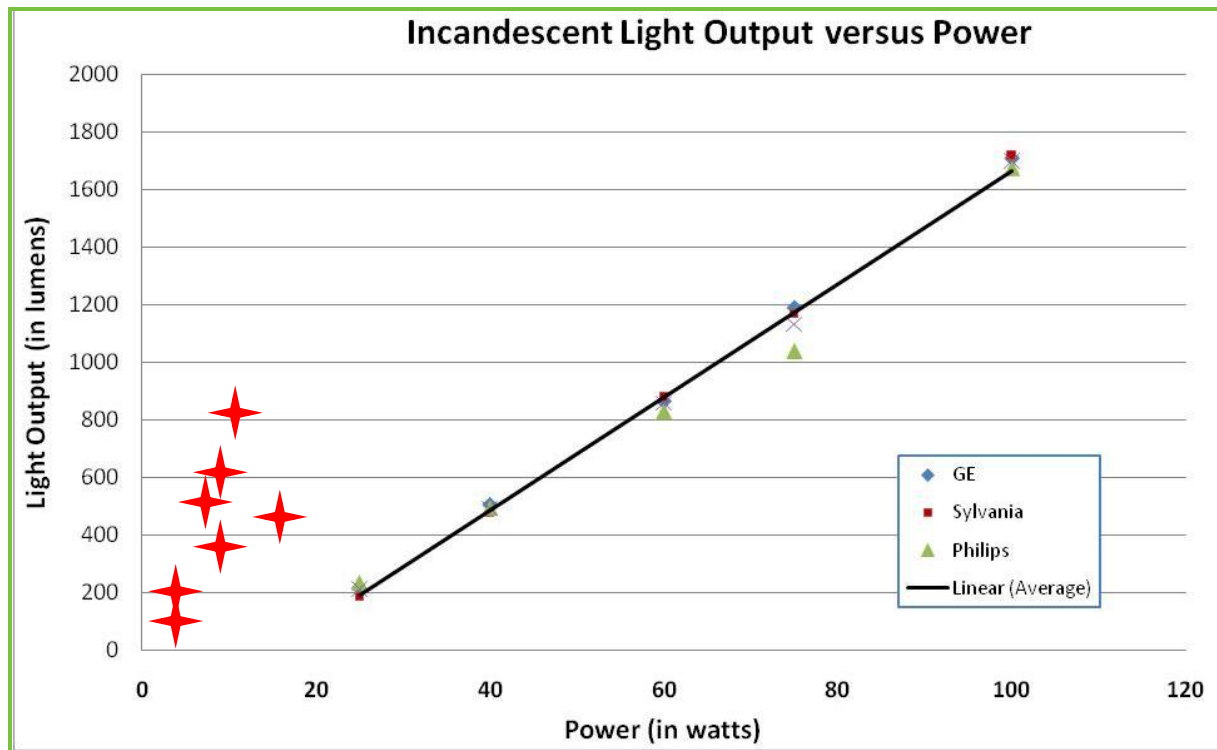
LED Light Output – “Equivalent” to conventional sources?

- LED devices have highly directional light output unlike conventional light sources
- In directional fixtures such as downlights, this results in much less wasted light trapped in the fixture



The Word “Equivalent”

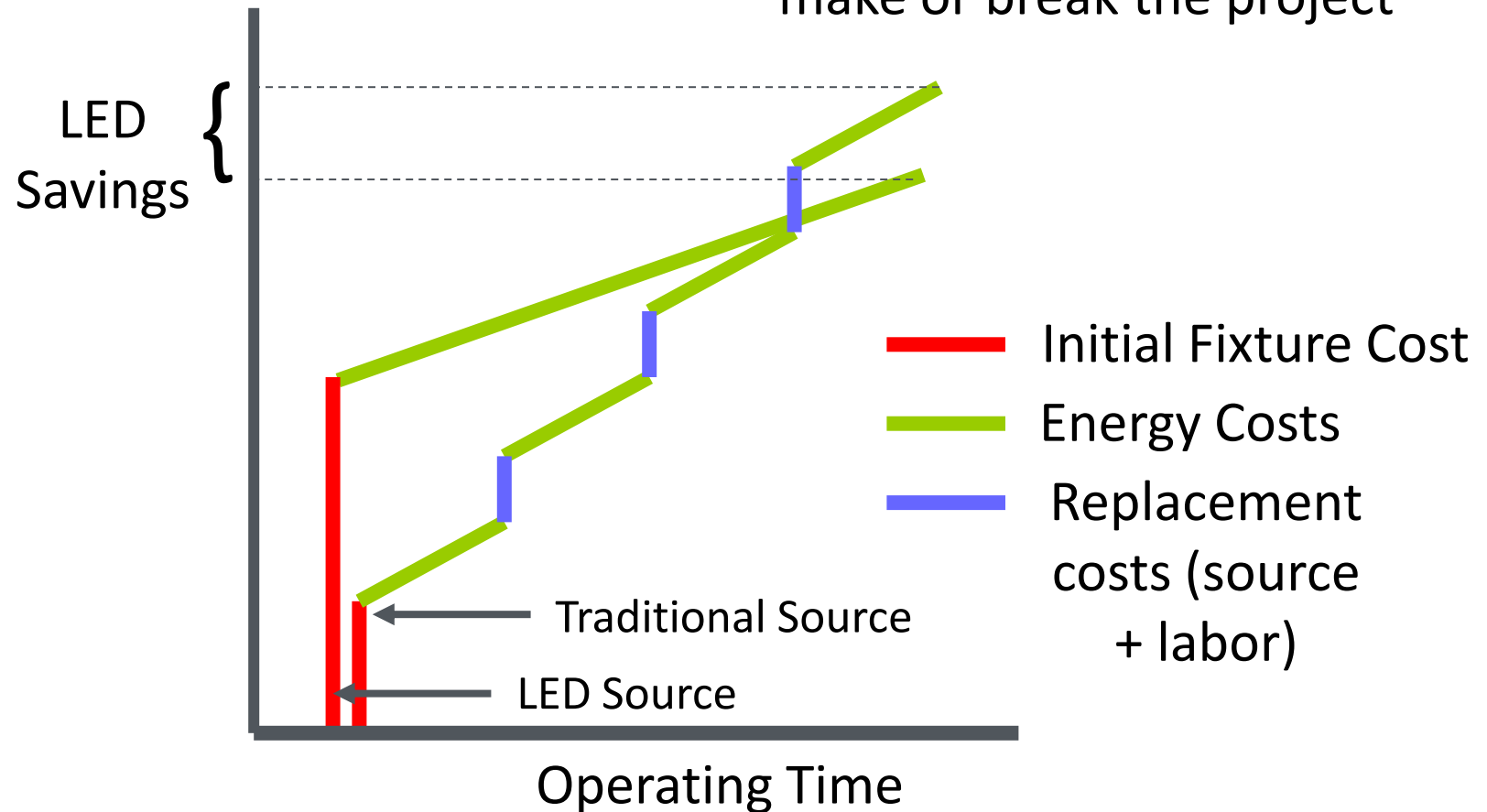
LED based lamp light output has a non-linear relationship
due to the different lamp's power (wattage)



Source: LED Transformations

LED Economics

Many times, maintenance costs
make or break the project



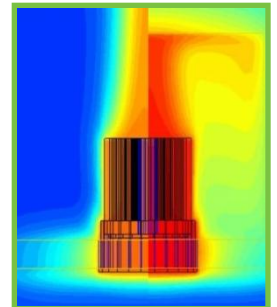
Dimming

- Because LED systems work differently from those of incandescent lamps, dimming is often an issue
- LED drivers must be designed to be compatible with line-voltage dimmers (of which there are many types)
 - Many line-voltage products not compatible (like CFLs) with certain dimmers
 - Many low voltage LED systems with certain step-down transformers are not compatible with certain dimmers
- One dimmer manufacturer provides a matrix showing compatibility and functionality with various manufacturers' luminaires/or drivers



Manufacturer	Model	Description	Dimming Range*	Compatible Product?
	Hi-lume LED driver	Driver	100% - 1%	YES
	Xtanium Current Driver	Current Driver	Not Specified	YES
	Xtanium PWM Driver	PWM Driver	100% - Off	YES
	eW PowerCore	Strip Light	100% - 15%	YES
	eW Profile - 11"	Under Cabinet Light	100% - 15%	YES
	eW Profile - 41"	Under Cabinet Light	100% - 15%	YES
	eW Downlight	Downlight	100% - 15%	YES
	Downlight	6" Downlight	100% - 5%	YES
	LR4	4" Downlight	100% - 20%	YES
	LR6	6" Downlight	100% - 20%	YES
	LR6 - 230V	6" Downlight	100% - 20%	YES
	LR24	24" x 24"	100% - 5%	YES
	Tetra dimming module	Driver	Not Specified	YES
	LED Cove Light	Cove Light	100% - 3%	YES
	Downlight	Downlight	Not Specified	YES
	LED-18-350-120-D	Driver	100% - 0.1%	YES
	LED-36-700-120-D	Driver	100% - 0.1%	YES
	Calculte 10W	Downlight	N/A	YES
	Calculte 20W	Downlight	N/A	YES
	Par 30	Par 30 lamp	Not Specified	YES
	OT Dim	Driver	100% - Off	YES








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One Way to Determine What's Good - CALiPER

Results from Round 9 CALiPER testing (October 2009) show that a large number of LED replacement lamp product manufacturers are still not providing accurate performance data

Table 4. CALiPER ROUND 9 – Replacement Lamp Manufacturer Claims

Sample Type and CALiPER Reference	Manufacturer Claims	Actual Performance Level (e.g. Light Output, Efficacy, CBCP, Beam Angle)	Provides Accurate Product Reporting	
Replacement Lamp (MR16) 09-80	180 lm, (54-69 lm/W) Eq. to 35W halogen	165 lm, 50 lm/W 304 cd, 31° Less than average 20W halogen	NO	
Replacement Lamp (R20) 09-78	230 lm, (32 lm/W) 7W=35W	263 lm, 42 lm/W 944 cd, 25° Exceeds average 35W halogen	YES	
Replacement Lamp (R30) 09-64	Replaces 45W (450 lm, 128 lm/W) CRI=84, 30° beam	186 lm, 54 lm/W CRI=71, 695 cd, 20° Less than 20W eq.	NO	
Replacement Lamp (PAR30) 09-76	Eq. to 75W Incand. 530 lm, 70 lm/W 60-70° beam	468 lm, 59 lm/W 190 cd, 100° Eq. to 50W R30	NO	
Replacement Lamp (PAR38) 09-63	Replaces 45W (450 lm, 90 lm/W)	289 lm, 58 lm/W 902 cd, 22° Less than 25W eq.	NO	
Replacement Lamp (A-lamp) 09-60	260 lm, (34.6 lm/W) Replaces 40W incandescent	251 lm, 34 lm/W Eq. to 25W incandescent	NO	
Replacement Lamp (A-lamp) 09-77	155 lm, (22 lm/W) Eq. to 25W	208 lm, 33 lm/W Eq. to 25W incandescent	YES	
Replacement Lamp (Candelabra) 09-65	Replaces 40W (320 lm, 220 lm/W)	67 lm, 45 lm/W Less than average 15W incandescent	NO	
Replacement Lamp (Candelabra) 09-74	30 lm, (12 lm/W) "Uses less energy than a 15W candelabra"	31 lm, 17 lm/W Eq. to 7-15W night light	YES (possibly misleading)	

CALiPER results are available at:

<http://www1.eere.energy.gov/buildings/ssl/caliper.html>

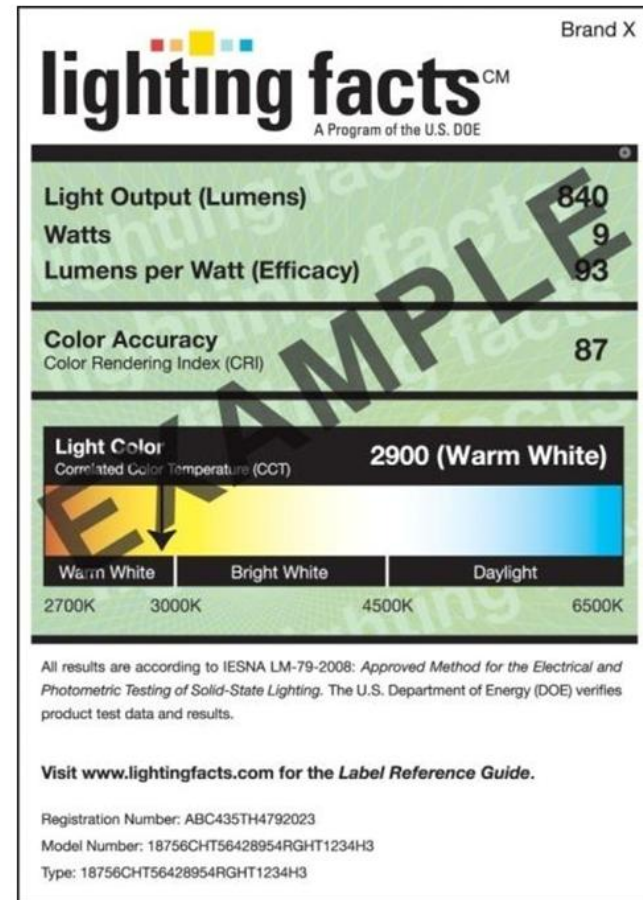
Another Way

Lighting Facts Label

Clear Representation of

- Light Output
 - Power
 - Efficacy
- Color
 - CRI
 - CCT

Results verified by third
party testing using LM-79
testing methods





Energy Star – SSL Luminaires General Requirements

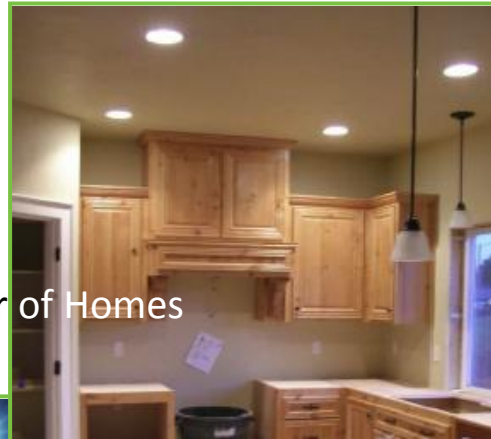
Highlights

- Indoor luminaires shall have a minimum CRI of 75
- Requires **zero** off-state power draw for the fixture; $\text{PFC} \geq 0.7$ residential, $\text{PFC} \geq 0.9$ commercial
- Lumen Maintenance:
 - Residential – 25k hrs Indoor, 35k hrs Outdoor
 - Commercial – 35k hrs commercial
- Luminaire efficacy requirements ratchet up over time to take into account technology improvements
- CCT shall be within one of the following groups: 2700K, 3000K, 3500K, 4000K, 4500K, 5000K, 5700K, 6500K

Gateway Program – Demonstrations in Various Applications

Demonstrations showcase high-performance LED products for general illumination in a variety of commercial and residential applications. Results provide real-world experience and data on state-of-the-art solid-state lighting (SSL) product performance and cost effectiveness.

Downlights Lane City Tour of Homes
Eugene, OR



And Finally...

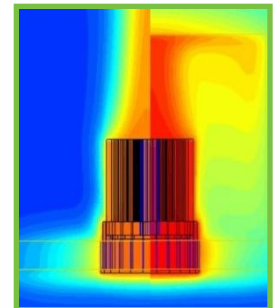
Third-party test results

- Don't just take the luminaire manufacturer's word
- Reputable photometric test labs
 - DOE certified for CALiPER testing
 - NVLAP certified for LM-79 testing

Warranty Policy

- Is there a written end-of-life policy? How will spares be made available?
- Do all system components from SSL manufacturers have a warranty and labor to fix/replace?
- How long is the warranty? What exactly is covered?

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Downlight – Good

Friendly's Restaurant, Westfield MA



Makes use of directionality

Installed 100 40W, 135 W
LED downlights

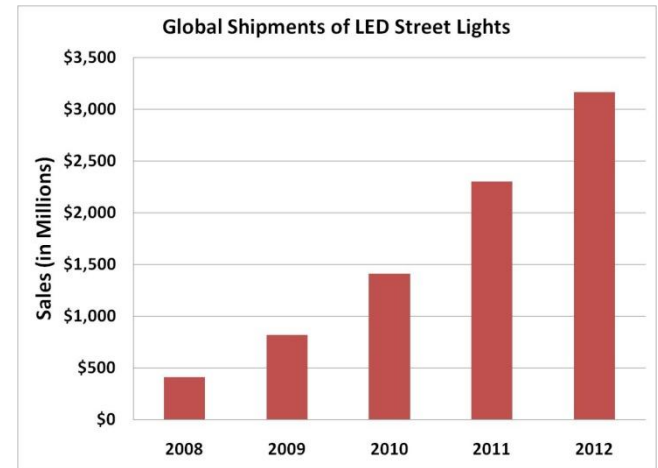
Source Cree

Street Lighting – Good



Source: Eric Haugaard, Ruud Lighting

Makes use of directionality



15% energy
savings over
previous HPS

Cove Lighting – Good



Source: GreenLight Initiative

Task Lights / Bollards – Good



**Makes use of directionality
and small form factor**

Incandescent Replacements – Good and Bad

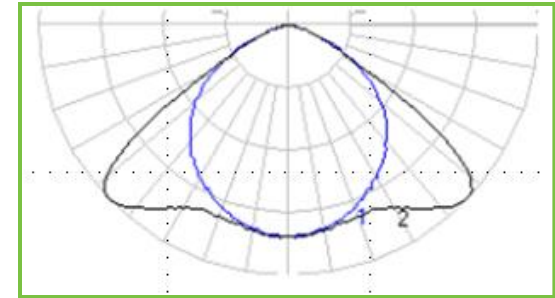
Wide range of product performance available, from good to poor



Makes use of small form factor and high efficacy

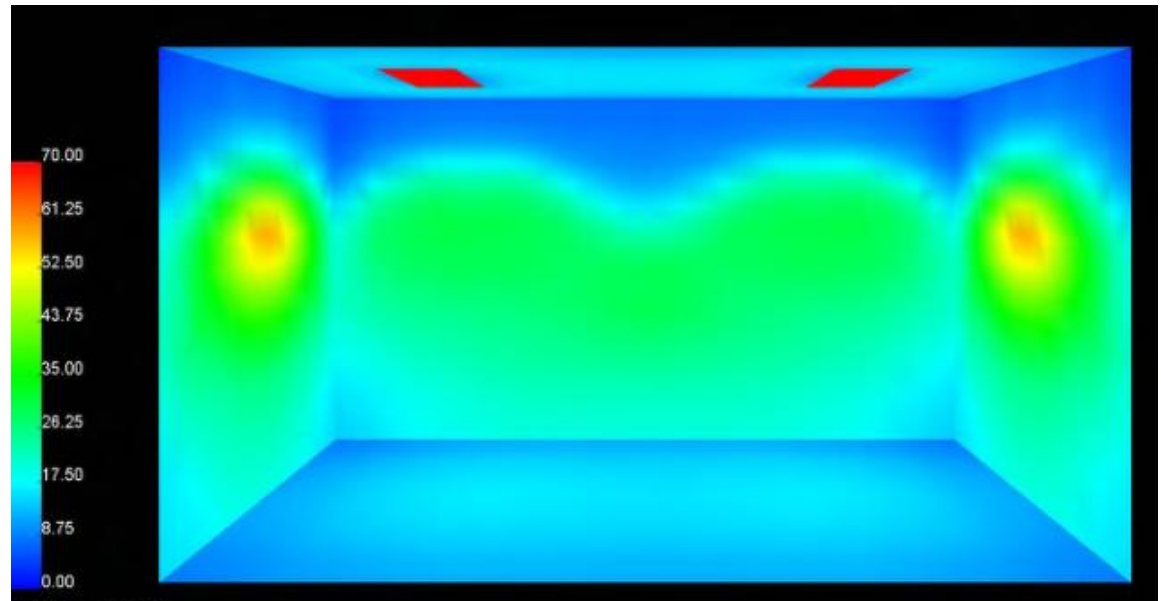
Fluorescent Replacements – Depends

2x4 parabolic louver
Fluorescent T8



0.92 LLD
0.95 LDD
0.88 BF (n/a)

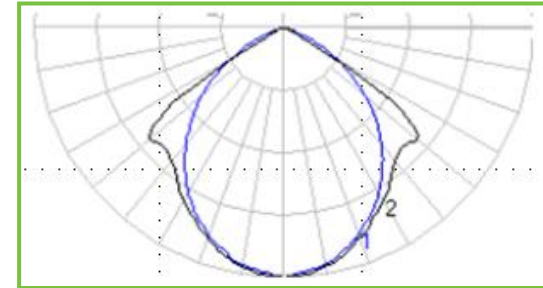
0.65 W/ft²
25 fc (average)
1.9 max/min



Source: Tuenge & Myer, DOE PNNL

Fluorescent Replacements – Depends

2x4 parabolic louver
LED Replacements



0.70 LLD

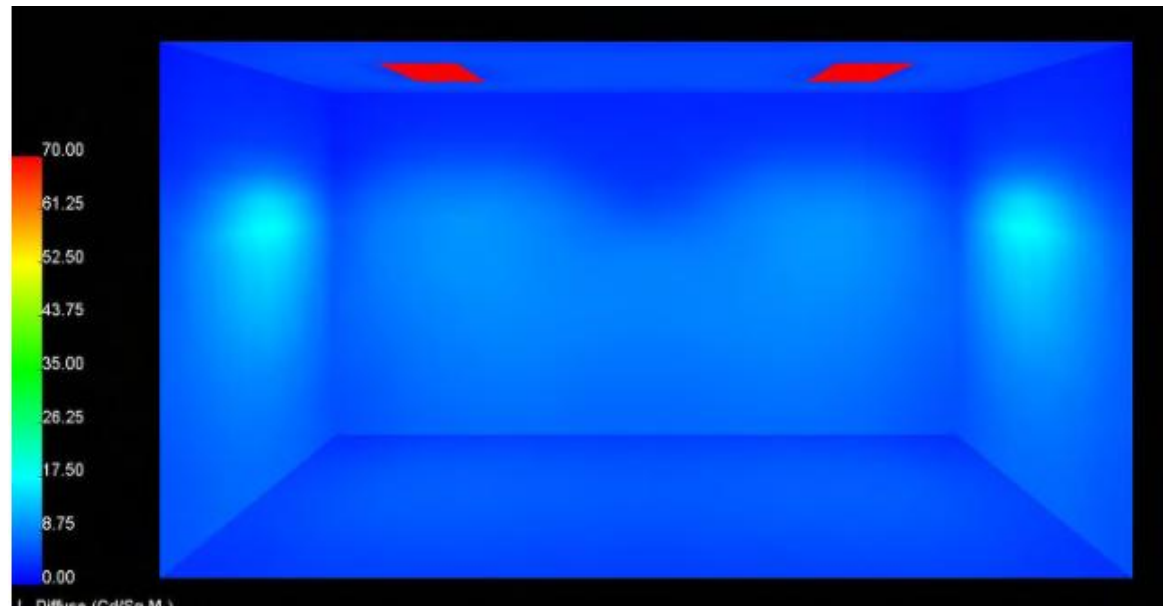
0.95 LDD

1.00 BF

0.44 W/ft²

10 fc (average)

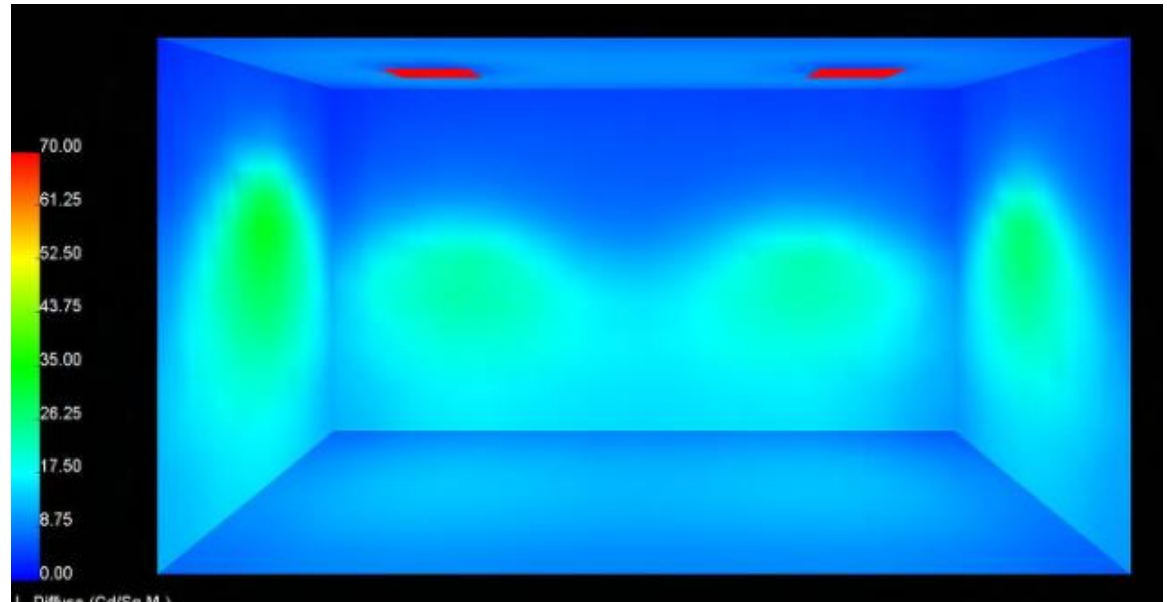
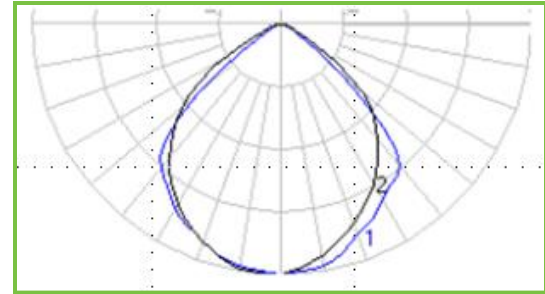
2.3 max/min



Source: Tuenge & Myer, DOE PNNL

Fluorescent Replacements – Depends

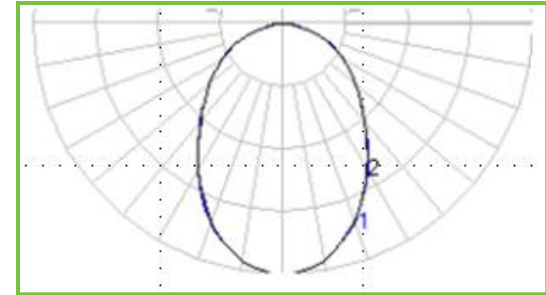
2x2 parabolic
Fluorescent T8U



Source: Tuenge & Myer, DOE PNNL

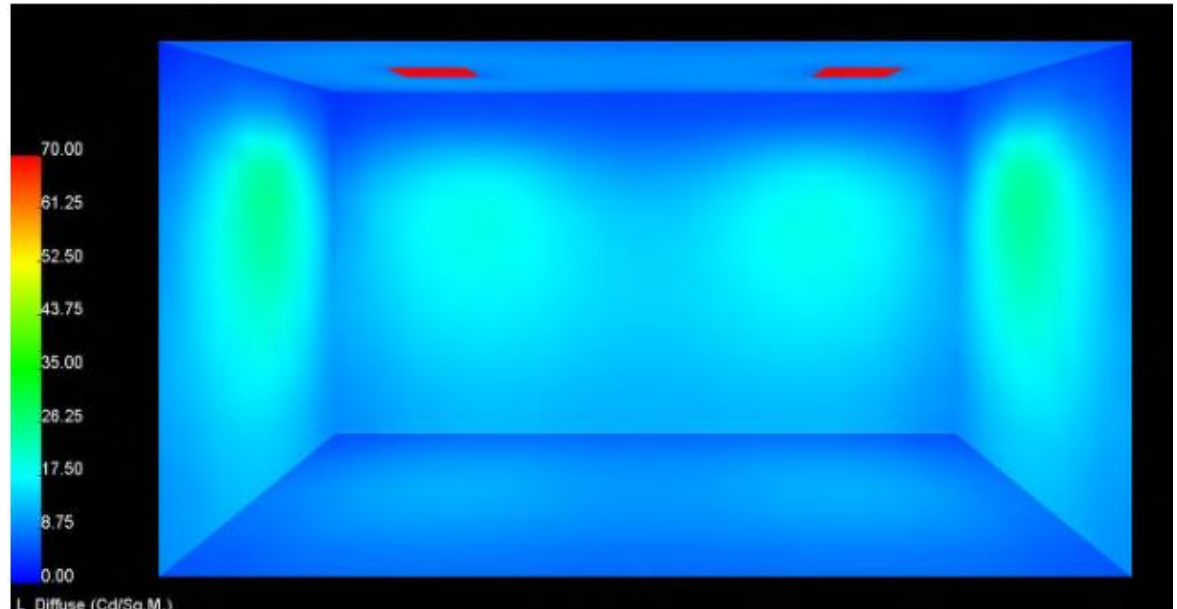
Fluorescent Replacements – Depends

2x2 lensed
Integral LED



0.70 LLD
0.95 LDD
1.00 BF

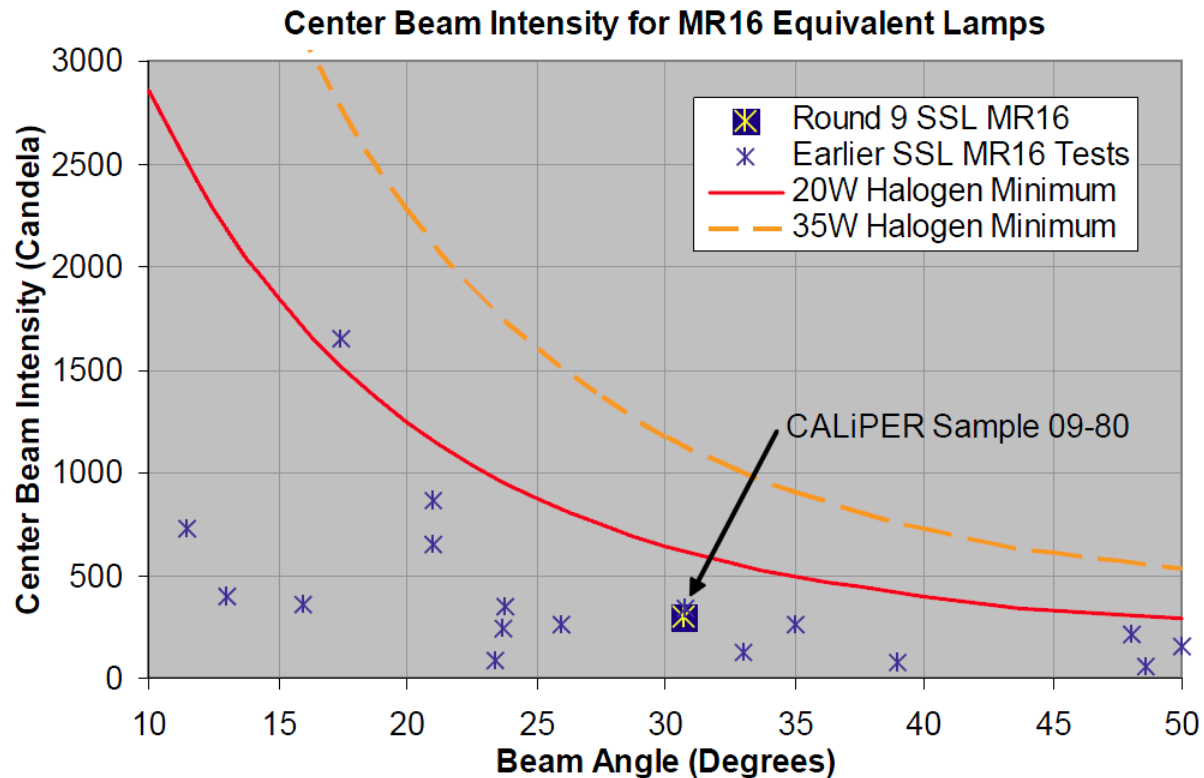
0.45 W/ft²
17 fc (average)
2.6 max/min



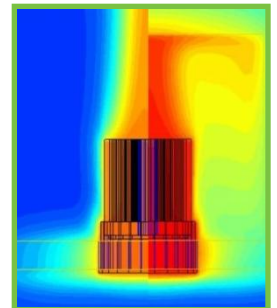
Source: Tuenge & Myer, DOE PNNL

High Power MR-16s – Not So Good

Halogen versus LED-based MR-16 test results



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Questions to Ask – Input/Output

- What is the delivered lumens at each correlated color temperature (CCT)? (Remember, flux and efficacy usually vary with CCT)
- What is the input power?
- Can the supplier provide LM-79 photometric reports and IES files from an independent testing lab?
- What is the luminaire efficiency?
- Can the vendor supply lumen depreciation data for the fixture?

Questions to Ask – Color

- What is the color rendering index (CRI) at each color temperature?
- How does the vendor ensure color consistency for fixtures built today or a year from now?
- Can the supplier provide test data demonstrating color stability over time?
- How far below the specified maximum LED junction temperature does the thermal management system keep the LEDs in all applications?
- Can the supplier provide at least two samples of the same CCT?
- Were chromaticity measurements performed according to LM-79 by an independent lab?



Source: Acuity Brands Lighting

Questions to Ask – Lifetime/Warranty

- Is there a written end-of-life policy, and how will spares be made available?
- How long is the warranty, and what exactly is covered?
 - Light output
 - Color shift
- Are components included? Is labor included?
- Has LM-80 testing been performed by the LED or LED module manufacturer, and what does it say about lumen maintenance?
- Does the vendor supply test data to verify that their system operates at a temperature and drive current consistent with those LM-80 test results?

Other Questions

- What are the electrical characteristics of the luminaire?
 - Power Factor
 - Off-state power consumption
 - Dimmable? With what controllers?
- Does the product have an applicable safety mark?
- Who is the manufacturer of the LED devices used in the luminaire?
- What type of technical support does the luminaire manufacturer offer?

And an Answer

Do not underestimate the use and practical application of simple
COMMON SENSE

- If it seems too good to be true, it probably is
- If you can't understand how a product could do "that," there is a high likelihood that it probably "doesn't"
- If nobody else's product does "that" maybe this product does not do it either

Which lamp would perform better? →



Where are LED-Based Products Appropriate?

- Outdoor area & street lighting
- Downlighting
- Task lighting
- Display lighting
- Cove lighting
- “Architainment” environments
- Other applications that make use of LED’s unique attributes
 - Small size
 - Directionality
 - Low temperature performance
 - Improved secondary optics performance due to die size
- As LED efficacy improves, applications will expand



A Lesson From History

- Think of how the microprocessor has changed the world over the last 30 years.



- The lighting world is about to undergo a change not seen since the invention of the incandescent lamp, and driven by that same semi-conductor industry.

Are you going to be ready for it?

DOE Resources

- SSL Quality Advocates / Lighting Facts^{CM} Label
- CALiPER Program
- Standards Development
- Lighting for Tomorrow
- Technical Information Network
- GATEWAY Demonstrations
- Next Generation LuminairesTM
- L-PrizeSM
- Municipal Solid-State Street Lighting Consortium

www.ssl.energy.gov

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ENERGY

Energy Efficiency &
Renewable Energy

Questions?

Thank You

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